TD-06-028

07/21/06

Test Solenoids
Expected Performance and Test Results
Part 2: PDST02-0

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In this note, results of testing the second test solenoid, PDST02-0, are presented. The solenoid is similar to PDST01-0, without a flux return, and wound using similar strand. The test systems were identical to those used for PDST01-1, except where specifically noted, and the test plan was fundamentally the same too. This report therefore follows the same outline as the first solenoid test report [1], within which the apparatus is described.

Geometrical Parameters of the Coil

Di	= 61.25 mm	Inner Diameter (above ground insulation)
Do	= 92.69 mm	Outer Diameter (average)
l	= 101.1 mm	Coil Length
N	= 2340	Number of turns in the coil
n	= 24	Number of Layers
R	= 31.82 Ohm	Coil resistance at room Temperature
L	= 150 mH	Coil inductance (without Iron Yoke)

Strand

Modified SSC inner strand was used to wind the coil. ML-insulated 0.808 mm SSC strand (IGC) from the same lot used in PDST01 was modified by rolling to the thickness of 0.56 mm. Insulation quality was slightly worse after rolling (hi-pot test gave ~600 V before, and ~300 V after rolling), but still acceptable. Dimensions after rolling became:

Bare strand	0.99 mm x 0.56 mm
Insulated strand	1.01 mm x 0.58 mm

Coil Compaction Factor

The compaction factor was calculated as for PDST01 and was slightly higher:

k = **0.754**

Specific Features

In the coil, voltage taps were made using fine shielded wire to provide additional noise reduction. This way of making voltage taps proved to be very unreliable: almost all taps were lost, at different stages of coil fabrication. As a result, coil protection was based entirely on the whole coil signal. Absence of the taps did not allow us to observe quench front propagation as was done in the case of PDST01 [1].

Heaters were installed with greater care though to ensure no air gaps or additional insulation thickness, for improved thermal conductivity to the coil.

Cold Test Data

PDST02-0 was tested at 4.22 K with the same apparatus as PDST01-1 in the stand 3 test dewar, from May 3 to May 4, in a single thermal cycle. The current history from the UNIX scan system is shown in Fig. 1.

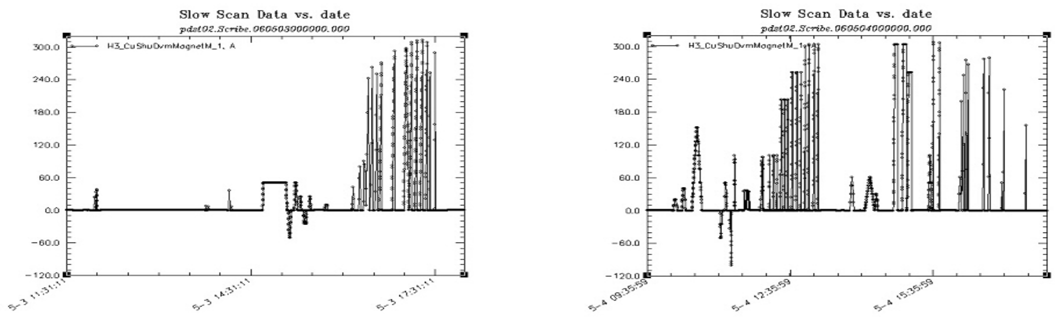

Fig. 1. Profile of PDST02 excitation current during cold testing.

Quench Current and Field Strength

Critical and maximal strand currents may be affected by rolling and annealing. Evaluation of the expected performance was made using an analytical representation of the critical surface (as measured by D. Turrioni on May 02, 2006) in the vicinity of the operating current: Ic = 519.5 – 137.5*(B-6.0)

The magnetic field distribution was also evaluated analytically [2], as was done for PDST01-0: intersection of the strand critical surface and the solenoid maximal magnetic field results in the following expected parameters at 4.2 K:

Iq	= 308.5 A	Quench Current
Bc	= 7.142 T	Central field at Quench
Bm	= 7.534 T	Maximum field in the coil
Eff	= 0.02315 T/A	Solenoid efficiency, Bc / Iq

The solenoid test temperature[1] was 4.22K, so no correction was needed for differences in test temperature, as was made in the case of PDST01-0. The correction for strand self-field makes the expected current ~ 0.5 % higher: 310.0 A. The quench history is shown in Table 1: This solenoid did show some training, but reached maximal field after 4 quenches. The first quench current was 10% below the maximum value. Following training, the quench current was found to have weak dependence on ramp rate, falling by only 4 % from 2 A/s to 16 A/s.

Table 1. PDST02-0 quench currents during training and ramp rate studies

Quench #	Ramp Rate [A/s]	Quench Current [A]
1	2	283.0
2	2	292.7
3	2	301.0
4	2	310.4
5	2	311.1
6	2	311.2
7	4	310.2
8	8	306.3
9	16	298.5

[1] Following PDST01-0 test, the power leads were upgraded; the first version required high liquid level for the superconducting leads, which resulted in higher pressure and helium temperature. PDST01-1, PDST02 and PDST03 tests were conducted under very stable 4.22K temperature conditions with the 2nd version.

The measured quench current is in good agreement (0.4% high) with the predicted value. Comments in [1] on the accuracy of measured quench current apply to this test also.

Heater-Induced Quench Tests

The quench heater location and connection schemes were the same as for PDST01. More care was taken to avoid possible air gaps between the heaters and the coil, thought to be a reason for the extra delay in quenching after initiating the heaters. Fig. 2 below compares the measured delay of coil quenching, at different levels of current in the coil, with the expected delay at 300 A [3]. In comparison with what was done for PDST01, the model of heat propagation was modified by taking into account the total surface of the heater, rather than just the surface of the resistive element. In this case we enjoy good agreement between the measurement and the prediction, which was not the case in [1].

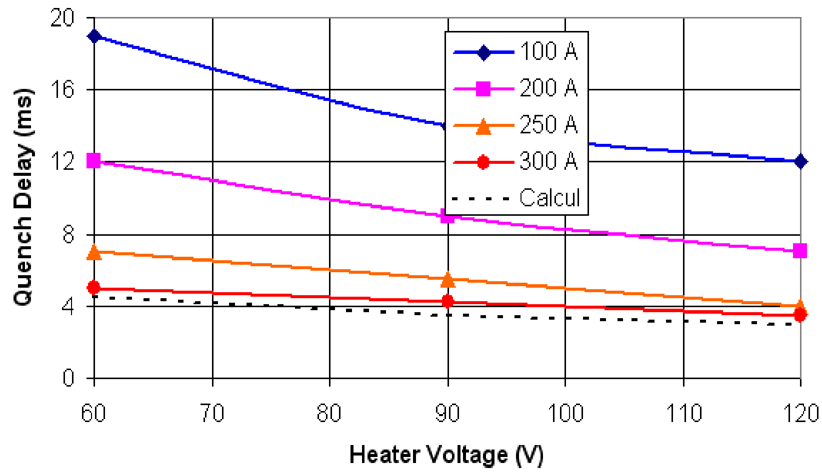

Fig. 2: Quench delay as a function of heater voltage, measured at different solenoid currents while increasing heater voltage slowly, and calculated for Icoil = 300 A.

DC Power Deposition Test

A DC power deposition test was performed similar to what was made for PDST01, but with more care taken to slowly step up the heater voltage at fixed solenoid currents. At a coil current of 300 A (~3 % below the quench level) the heater could dissipate ~ 0.25 W before the coil quenched. At I = 250 A (~ 20 % below Iq) this power reached 1.2 W. This data can help define the ultimate heat load that the solenoid can survive.

Solenoid Survival Test

No solenoid survival test was conducted on PDST02, since the conductor used, details of construction, and major parameters were nearly identical to PDST01 (flattening of the strand is not expected to alter its quench development properties).

Stress in the Solenoid

The pattern of stress relief during excitation was similar to that of PDST01. The linear fits to coil resistance versus squared current for the two active gauges are shown below:

Fits of R vs I^2	Gage A	Gage B
$dR/d\,I^2$ (10^{-6} Ohm/A^2)	1.18+/-0.01	1.19+/-0.01

These results are consistent with what was obtained for PDST01 ([1], Fig 13a).

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Magnetic Field Measurements

Magnetic measurements on PDST02 focused on magnetization properties of the conductor. Warm measurements prior to the cold test cycle were performed using the Kepko bipolar power supply to excite the coil with alternately positive, zero, negative, zero currents of 1 Ampere magnitude, with the Hall probe located at the solenoid center. This identified a magnetized element (~0.5 G level), the machined stainless steel Hall probe support, which was replaced by an aluminum piece. Subsequent checks found a residual magnetization at the level of 0.1 G, which was deemed sufficiently small background for measuring the conductor magnetization properties.

"Warm" and "cold" Z-scans were performed to locate the solenoid center, and to check the transfer functions; these are shown in Fig. 3 below. The warm data were taken prior to correcting the ferromagnetic anomaly in the probe support, while the cold data were taken after this was corrected, at 50 Amperes in the coil. From the cold z-scan, the peak transfer function is found to be 234.2 G/A, about 1% higher than the predicted value of 231.5 G/A.

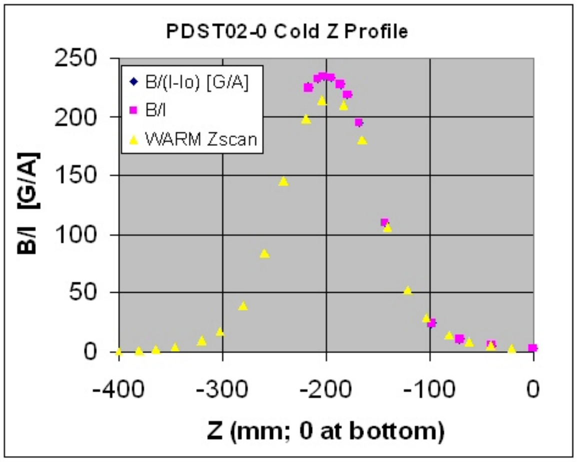
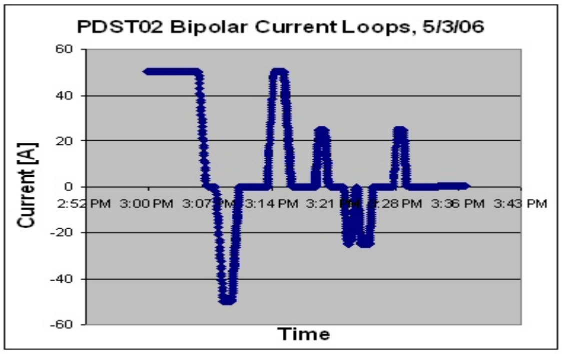


Fig. 3: Transfer function B/I versus probe position from warm and cold z-scans.

Differences between the calculated and measured transfer functions can result from residual magnetization of the coil (not included in the calculation). In an attempt to clarify this issue, some study of the coil magnetization was made with the Hall probe centered in the solenoid; these measurements were limited to 3 T, or current of about 125 A. Magnetization studies were made simultaneously with studies of quench behavior (see Fig. 1); because the coil temperature profile following a quench is not known or predicted, the remnant magnetization state in the coil can not be predicted precisely.

The solenoid was excited with a set of bi-polar stair-step loops of alternating polarity to current plateaus up to 50A. For each loop, a stop was made at "zero" current. The residual field at zero current is shown in Fig. 4: the difference in the remnant field is about 65 Gauss. The last points in the graph were taken with the Quench Protection system tripped off and then with the Power Supply turned off. The data reflect that there is a small but finite current – reproducible and the same for both polarity settings – at the nominal "zero" setting. Additional investigation of the current readout accuracy is required here.



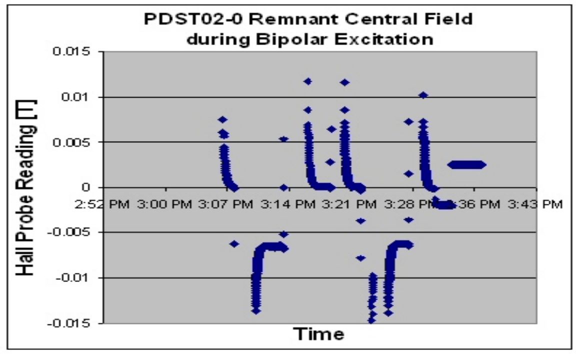


Fig. 4. Solenoid central field at zero current during bipolar excitation study (right).

Power supply protection diodes were installed after the low current bi-polar measurements, so further hysteresis studies were performed with stair-step ramps up and down with a single power supply polarity. The duration of the current plateaus were made 30 seconds, long enough for the current to stabilize at the same value on both the up and down ramp. The widths of the hysteresis loop are shown as a function of the plateau current in Fig. 5 below, where we have determined the difference in magnetic field strength at a given plateau current between the down-going and the up-going legs of the hysteresis curve. Clearly the response is complex, and depends upon the step size and maximum current of the loop. This probably results from the superposition of many "shells" of magnetized conductor at differing radius, whose local field may or may not exceed Hc_1 on a given loop - and therefore may or may not exhibit a reversible hysteresis behavior.

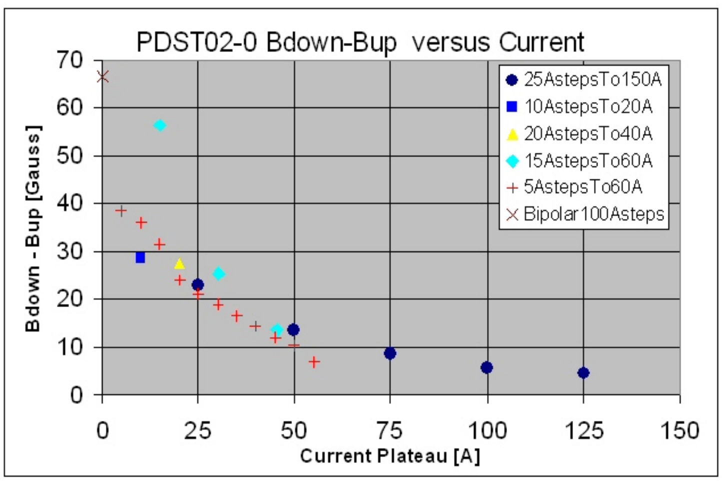


Fig. 5: Difference in solenoid central field versus stair-step current, [B↓–B↑], for unipolar hysteresis loops of varying step size and maximum current.

Concluding Remarks

The second test solenoid demonstrated very similar performance to the first: flattening of the SSC strand increased the coil compaction factor slightly (1 %) and did not introduce any problems. Characteristics of mechanical stress and quench performance were consistent with expectations; the lack of working voltage taps prevented us from making quench development studies, so the full energy deposition test was not performed. More careful heater installation resulted in very good agreement with the predicted time for quench development. The central magnetic strength agrees within 1 % of the expected value; hysteresis data were successfully taken, but further analysis is required to understand the coil magnetization behavior.

References

1. R. Carcagno, et al, Test Solenoids: Expected Performance and Test Results, Part 1: PDST01-0 and PDST01-1, TD-06-027, FNAL, July 2006.
2. I. Terechkine, Proton Driver Front End. Warm Section Focusing Solenoid, TD-05-037, FNAL, August 2005
3. I. Terechkine, Solenoid Quench Heater, TD-06-006, FNAL, February 2006